Civil Engineering Infrastructures Journal xx,xx

DOI: 10.22059/ceij.2025.387273.2206

Improvement the pavement Soil Subgrade Properties with Polypropylene Fibers and Its Effect on the Thickness of Pavement Layers: An Experimental Study.

Beshoy Maher Hakeem.

Lecturer, Civil Engineering Department, Higher Institute of Engineering and Technology, New Minya, Egypt. Email: civileng_beshoy@yahoo.com. http://orcid.org/0000-0003-4286-3202

Corresponding Author:

Beshoy Maher Hakeem.

Email: civileng_beshoy@yahoo.com.

Received: 12/01/2025

Revised: 15/08/2025

Accepted: 28/09/2025

Received: Revised: Accepted:

ABSTRACT: From an engineering perspective, certain locations could not be suitable for building operations since there aren't enough acceptable soils. Soil reinforcement has been used to enhance the characteristics of ground soil especially for engineering projects. In this study, Fibers (polypropylene fiber) were used and mixed with soil at random to strengthen the subgrade soils in flexible pavements. For the purpose of increasing soil strength, fibers were added in different amounts (0.25–1.5%) by the soil's dry weight. To evaluate the compressive strength and shear parameters of subgrade soil, California Bearing Ratio (CBR) test, both the unconfined compression test and the modified proctor test were conducted. The results revealed that the unconfined compressive strength increases by 66.44 %, the soil subgrade cohesion improves 108.98 %, the CBR value increased by 115.7% in the case of unsoaked condition, and in case of soaked state the maximum CBR value increased by 151.19% are found at 1.0 % polypropylene fiber content. However, as more fiber is added to the soil, the percentage improvement starts to decrease. Additionally, the results demonstrate that the optimal moisture content increases and the maximum dry density decreases as the fiber content increases. Fibres addition increases the soil's CBR value, which decreases the pavement structure's thickness by 25 % reduction in the thickness of AC layer, 37.5 % reduction in the thickness of base layer and consequently, its construction costs.

In addition, six preliminary correlations are established between the fiber content and the expected percentage increase in compressive strength, CBR value, cohesion, optimum moisture content, and percentage reduction in maximum dry density.

Furthermore, the results showed that adding 1.0% polypropylene fiber to the subgrade soil decreased both the thickness of the pavement layer and the pavement's cost.

Keywords: Unconfined compressive strength, CBR, Cohesion, Polypropylene Fiber, Reinforced Soil.

1. Introduction

Soil reinforcement has been employed in geotechnical engineering for improving ground soil properties, particularly for engineering projects. The stability of a structure depends on the subsurface soil's strength characteristics. Numerous tests were conducted using both regular soil and dirt reinforced with fibers. The CBR value of reinforced soil was shown to increase with the addition of more bamboo fiber; this increase is significant at a fiber dose of 1.2%. Brahmachary and Rokonuzzaman (2018)

Singh and Jamatia (2020) investigated the effect of two different fiber kinds on the subgrade characteristics of pavement soil. Considering the results, the unconfined compression strength increases when fiber is added up to a specific percentage before decreasing as the fiber concentration rises.

One of the key measures used to evaluate the bearing capacity of the subbase and subgrade is the California Bearing Ratio (CBR) test. According to Dobrzycki (2023), the effect of compaction of samples with and without cement and fiber additions on the value of CBR was determined. The addition of polypropylene fibers has a considerably greater effect on the CBR values for samples compacted using the standard proctor method.

Kunyong and Frederick (2017) investigated the influence of different proportions of clay minerals on the moisture density relationship and index properties of clay soils. They used 11 distinct remolded samples created by combining double mixtures of commercially available powdered kaolinite, montmorillonite, and quartz in proportions of 30%, 50%, 70%, and 100% based on dry unit weight to investigate the relationship between different proportions of clay minerals with index properties and compaction characteristics of clay soils. The results indicated that when the percentage of clay minerals increases, Atterberg limits often rise as well, although the increase is more pronounced in mixes that are dominated by montmorillonite. In soils dominated by either kaolin or montmorillonite, the maximum dry density decreases as the latter increases. Also, in both soils dominated by kaolin and montmorillonite, the optimum moisture content increases as the clay content increases.

During road construction, weak lateritic subgrades are frequently found. According to Lawer et al. (2021) natural fibers dispersed at random were examined as a possible reinforcement for low volume highways' weak lateritic subgrade soil. The findings showed that when the fiber was added, the soaked CBR increased from 7 to a maximum of 18, 22, and 25 for fiber lengths of 30 mm, 60 mm, and 90 mm, respectively.

Wei et al. (2018) investigated the impact of sisal fiber and polyurethane addition on the mechanical behaviour and strength of sand. Soil was reinforced with sisal fiber (SF) and water-based polyurethane (PU). The findings showed that, within our test range, the fiber and polymer contents of specimens improve both their post-peak strength and unconfined compressive strength (UCS). The ductility of specimens is greatly increased by the addition of fiber and polymer.

Experimental investigation of glass fiber-reinforced clayey soil was carried out by Patel (2022). The compaction characteristics (OMC and MDU) of clayey soil are slightly changed by the addition of glass fibers. Clayey soil's ductility is continuously increased by the addition of glass fiber.

To investigate the possibility of employing glass fibers as discrete random reinforcement to strengthen expanded subgrade soil for pavement application. The dried soil had a weight proportion of 0.25 to 1.0% fiber. Free swell, Unconfined Compressive Strength (UCS), Indirect Tensile Strength (ITS), and California Bearing Ratio (CBR) were among the tests performed on both unreinforced and reinforced expansive soil specimens. The soil's hardness rose and its tendency to swell decreased in proportion to the quantity of employed fibre. Rabab'ah et al. (2021).

Several tests were conducted on the silty sand soil fiber mixture to ascertain the soil's strength after stabilization. The findings of the CBR test indicated that increasing the fiber content raised the CBR value, while the maximum dry unit weight (MDD) values decreased while the optimum moisture content (OMC) increased with the addition of fibers. Balreddy et al. (2024)

One technique for improving soil for large-scale projects is the addition of fibers, either natural or artificial, to subgrade soils. Natural inorganic fibers, basalt fibers are widely used in a variety of industries. The resilience and California bearing ratio capabilities of the stabilized soil (soil+basalt) sample are investigated in order to comprehend the polypropylene characteristics. According to the experimental findings, adding basalt fiber to soil effectively increases its strength. Prathyusha and Kumar (2020)

Flexible pavements are divided into layers, which include the base course layer sub- base layer, surface course layer, and subgrade layer. According to Modha and Shah (2019) coir fibers are used as reinforcement and its effects on the various index properties, the results showed that the effective use of coir waste can give rise to rural economies and lead to beneficial effects in engineering construction.

Patel and Singh (2017) investigated the relationship between CBR and secant modulus and various fiber content, fiber length, compacted moisture content, and soaking time. With only a slight decrease in MDU and a negligible rise in OMC with an increase in fiber content, the addition of glass fiber has little effect on the cohesive soil's compaction behaviour.

The subgrade soils experience traffic-induced stress over their service life, and because they are particle, they typically aren't able to withstand this stress. The cyclic stress resistance of reinforced and unreinforced subgrade soils was evaluated by Aneke et al. in 2023. For soil specimens reinforced with 0.5% fiber content, the fiber inclusions increased the shear stress hysteresis loop; above this point, the loop shifted backward, resulting in poor resistance to the axial strain.

Madrid et al. (2024) found that adding fibers to expansive clayey subgrade soils improved their performance. The findings showed that adding fibers greatly reduced soil swelling while increasing its strength modulus.

Zemouli et al. (2024) describe how adding polypropylene fiber to the ideal CKD-soil mixture impacts the soil's unconfined compressive strength and compaction behavior. The analysis's findings demonstrate that adding cement kiln dust (CKD) greatly increased the strength, workability, and compaction of the soil under study. The clay's resistance to compression is also strengthened by the addition of polypropylene fibers, which offers promising prospects for lessening the challenges posed by expansive soils in civil engineering applications.

According to Bu. Et al. (2024) to enhance the water-retaining property and cracking resistance of soil sisal fiber and polyacrylamide were added. According to the findings, 0.6% and 0.5% of sisal fiber and polyacrylamide, respectively, are ideal for improving clayey soil's ability to absorb water and prevent cracking.

Abd Al-Kaream et al. (2022) investigated if some polypropylene fibers in various ratios might be used as soil reinforcement. The findings showed that the maximum dry unit weight and specific gravity decrease as the amount of polypropylene fiber increases. When polypropylene fiber is combined with soil at varying percentages, the unconfined compressive strength and the liquid and plastic limits also increase.

Adegoke et al. (2025) evaluated the effects of polypropylene fiber reinforcing and lime stabilization on unpaved road layers using laboratory tests of CBR, tensile strength, and load-bearing capabilities under both static and dynamic conditions. The findings showed that fiber-reinforced samples with a 1.8% content surpassed the minimum subgrade standards (CBR > 8%) in both soaked and unsoaked conditions. Tensile strength peaked at 37.45 kPa (1.8% strand fibers) and 30.8 kPa (2.4% discontinuous fibers).

In 2020, Shamim presented an experimental study that used geosynthetic materials to improve the subgrade soil of flexible pavement. The results showed that the CBR value gradually decreases after increasing up to 6 cm from the top. By strengthening soil, the CBR value rises by roughly 54% and 35%, respectively, for unsoaked and soaked soil at a depth of 6 cm.

The influence of adding steel and polypropylene fibers to the surface course of airfield concrete pavements were investigated, according to Armeni and Plati (2025). According to the results, there were notable variations in the highest percentage increase in flexural strength brought about by the inclusion of fibers. Particularly for polypropylene fibers, this increase ranges from 7% to 62%, with an average of 24%. The maximal flexural strength varied significantly with the addition of steel fibers, ranging from 24% to 92%, with an average of 49%. It was discovered that adding polypropylene fibers increased the maximum flexural strength on average by around half of what adding steel fibers achieved.

Soil reinforcement, mechanical stabilization, and chemical stabilization are all common ground stabilization techniques that have been the subject of prior research. However, as society becomes more concerned with sustainable products and materials, these techniques are becoming less common due to their high cost and environmental impacts. In order to ascertain how fiber influences the values of unconfined compressive strength, California Bearing Ratio, Modified Proctor test results, and soil subgrade cohesion, an experimental investigation was conducted. Furthermore, six initial correlations are shown between the fiber content and the anticipated percentage increase in cohesion, optimum moisture level, CBR value, compressive strength, and maximum dry density. Also, this research also focused on reducing the thickness of the paving layer and thus reducing the cost. The limitations of this study: Used fibers (polypropylene fibre) to improve the soil subgrade properties, this study focused on flexible pavement, medium clay soil only used in this study, the fibre length is 12 mm, and having diameter 0.018 mm.

Objective of the Present Study

a) To study the effect of fiber content, this was used to improve the soil subgrade properties.
b) To improve the CBR of subgrade soil this decreases the pavement structure's thickness and, consequently, its construction costs.
c) The goal of this study is to use fiber to improve the characteristics of medium subgrade soil. The novelty in this research is to introduce some of the correlations between fiber content and the expected percentage increase in compressive strength, CBR value, cohesion, OMC, and percentage reduction in maximum dry density.
d) These fibers have advantages over other kinds of materials used in soil improvement in terms of cost, mass availability, and environmental friendliness.

2. Experimental Programme

For this study, a comprehensive experimental plan was employed by the Soil Mechanics Laboratory at the Higher Institute of Engineering and Technology, New Minya, and the Geotechnical Engineering Laboratory at the Faculty of Engineering, EL-Minia University, to enhance the unconfined compressive strength, California bearing ratio, Modified

Proctor test results, and cohesion of soil subgrade. Six different percentage of fiber content (0.25–1.5%) by dry weight of soil were added to natural soil. This study presents an analysis and report of the test findings and observations made during the studies.

2.1. Materials Used.

The medium clay soil used in this research was collected from a Damaris, EL-Minya area. The obtained soil was subsequently dried in order to ascertain the engineering characteristics.

In the experiments, the soil subgrade is reinforced using polypropylene fiber. One of the synthetic fibers that is most widely accessible is polypropylene. The fibers made of polypropylene are hydrophobic and noncorrosive, and they can withstand attacks from chemicals, alkalis, and chlorides.

2.1.1. Sika Fibers.
(Monofilament Polypropylene Fibers)

Sika Fiber is a monofilament polypropylene additive fiber that improves the surface characteristics and durability of hardened cementitious products while lowering the incidence of plastic shrinkage and plastic settlement cracks.

The fibers are single, incredibly fine filaments with a diameter of 18 microns that are cut to a length of 12 mm in compliance with the standards for surface appearance and maximum aggregate size. To enhance initial dispersion and bond, a surfactant is applied to the fibers.

According to the product data sheet (2024), Sika Fiber is utilized in shotcrete/Gunite, precast concrete, water retaining structures, and internal floor flabs. Monofilament polypropylene fiber (0.25%, 0.50%, 0.75%, 1.0%, 1.25%, and 1.5% of the dry weight of soil) was utilized in this study to strengthen and enhance the characteristics of the subgrade soil. Figure 1 shows sika fiber from Sika Egypt for construction chemicals in Section #10 Block 13035 of El Abour City's First Industrial Zone (A). Table 1 lists the physical characteristics that the manufacturer provides for this fiber.

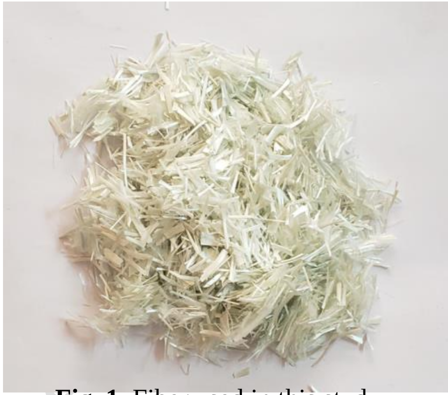
Fig. 1. Fiber used in this study.

Table 1. Physical Properties of Sika Fibers

Properties	Sika Fibers
Type	Monofilament
Colour	Natural
Diameter	0.018 mm
Length	12 mm
Density	0.91 gm nominal
Tensile Strength	350 N/mm^2
Elongation	> 80%
Absorption	Nil
Specific Surface Area	250 m^2/Kg
Thermal Conductivity	Low
Electrical Conductivity	Low
Acid Resistance	High
Alkali Resistance	100%

2.1.2. Soil subgrade.

The experiment is carried out on mixed soil samples that have been reinforced with polypropylene fiber. Several of tests were conducted to determine if the addition of fibres could increase the strength characteristics of the subgrade soil.

According to the Unified Soil Classification System, the soil employed in this study was categorized as CH and had a high compressibility form. Table 2 lists its physical characteristics.

Polypropylene fibers were homogeneously distributed and mixed with the soil after being sprayed at random into the soil mass at 0.25%, 0.50%, 0.75%,1.0%,1.25% and 1.50% of the soil dry weight. The mixing process was simplified by the use of a manual mixer. The soil-fibers mixing procedure for 0.50% fiber content is shown in Figure 2. Several investigations such as Mirzababaei et al., 2017; revealed similar fiber contents.

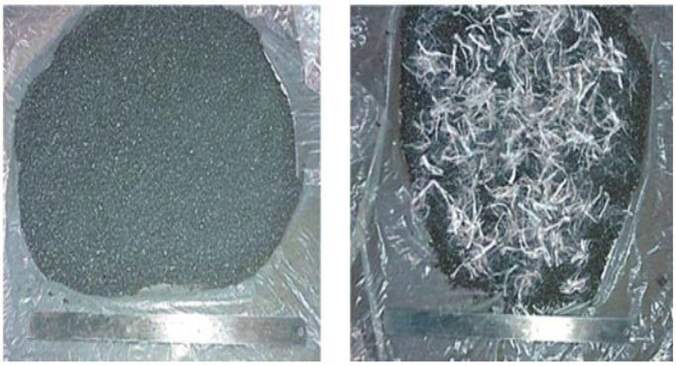

Fig. 2. Process of mixing soil and fiber.

Table 2. Geotechnical parameters of the clay that was used in this investigation.

Properties	Value
Liquid limit (L.L.)	50.72 %
Plastic limit (P.L.)	26.85 %
Plasticity index (P.I.)	23.87 %
Grain size analysis	Sand = 3.5 % Silt = 3.0 % Clay = 93.5 %
Classification of Soil (USCS)	CH
Specific gravity (Gs)	2.54
Maximum dry density (γ_{dry})	1.73 g/cm^3
Optimum moisture content	15.8 %
Cohesion (C)	0.49 Kg/cm^2
Angle of internal friction (Ø)	(≤2°) Negligible

2.1.3. Laboratory Tests on soil subgrade.

1- Unconfined compressive strength test.

In this experiment, the applied stresses on the base were tested using a proving ring with a 7 kN capacity. A universal compression machine was used to calibrate the proving ring. Between load and proving ring, four distinct regression equations were developed. The optimal curve fitting for each relationship was determined using a variety of mathematical functions, including exponential, linear, second-degree polynomial, hyperbolic, and logarithmic. Figure 3 shows the (R^2) values that came from fitting curves. It was discovered that the linear curve fitting equation has the highest value (R^2 = 0.999).

It was found that the calibration equation was as follows:

Load (kN) = 0.0045 × Proving ring reading – 0.093.

Fig. 3. Calibration chart of proving ring.

According to (ECP 202-2001, Edition 2007), the test specimens' unconfined compressive strength (q_u) was calculated. The sample is 76 mm long and has a diameter of 38 mm. According to (ECP 202-2001, Edition 2007), the specimens were then loaded at a displacement rate of 1.5 mm/min using an automatic loading machine until they failed.

The load ring and the vertical displacement dial gauge were set to zero. The test was performed in accordance with (ECP 202-2001, Edition 2007) using an electromechanical compression machine, shown in Figure 3, with accurate electronic control of the loading rate. The vertical displacement was measured until failure. The UCS was determined at failure. When the sample was about to fail, random longitudinal cracks formed at samples as shown in Figure. 4. Then stress –strain curves were drawn as discussed in this study.

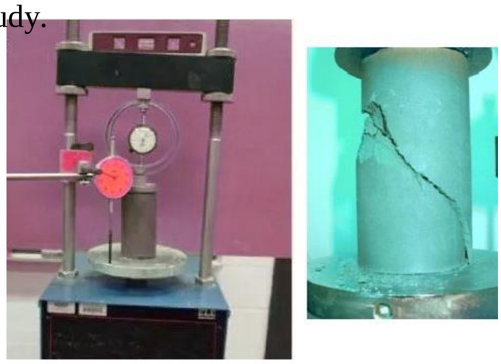

Fig. 4. Unconfined compressive strength test.

2- Modified proctor compaction test.

The moisture content and density of the compacted soil determine its geotechnical characteristics. The geotechnical characteristics of the soil are generally improved by a high degree of compaction, so it is important to get the appropriate degree of relative compaction required to achieve specified or desired soil characteristics. The Proctor test, also known as the moisture-density test, was created to determine the maximum dry densities (MDD) and optimal moisture contents (OMC) of both untreated compacted and treated stabilized soil mixtures.

The optimum moisture content and maximum dry density of the soil were ascertained by carrying out modified Proctor compaction tests, as illustrated in Figure 5. (ECP 202-2001, 2007 Edition).

Fig. 5. Modified proctor test.

3- California Bearing Ratio (CBR) tests.

Flexible pavement design makes extensive use of the CBR test. It is essentially a straightforward penetration test used to assess the strength of road subgrades. The CBR number indicates that the subgrade is weak, thus we must build a suitable thicker road pavement to disperse the wheel load across a greater area of the weak subgrade in order to prevent the weak subgrade material from deforming and causing the road pavement to fail. The soil sample measures 152 mm in diameter and 178 mm in length. The specimens were then loaded at a displacement rate of 1.0 mm/min using an automatic loading machine until they failed according to (ECP 202-2001, Edition 2007). CBR was tested in unsoaked and after soaking samples in water for four days as per (ECP 202-2001, Edition 2007) as shown in Figure 6.

Fig. 6. California Bearing Ratio test of soil samples.

4- Direct shear box tests.

The direct shear test was carried out utilizing a shear box measuring 60 mm by 60 mm and standard direct shear apparatus. Two metallic plates, two porous stones, two screws, a gripper disk, and a loading cap—where the typical stress is applied—make up the shear box. The specimen's horizontal strain is limited by the shear box, which can be square or circular in shape and allows shearing on a horizontal plane where the two metallic plates meet. A 60 mm square soil sample is subjected to shearing stress along a predetermined horizontal line until the specimen breaks. According to (ECP 202-2001, Edition 2007), the shearing device applies a constant displacement rate of roughly 1 mm/min. Figure 7 shows the experimental configuration.

Fig. 7. Direct shear box test for soil samples.

3. Results and Discussion.

3.1. Effect of Sika Fibers Reinforcement on compaction characteristics.

As mentioned in the preceding section, many soil samples were tested with and without polypropylene fibers to determine the strength of the soil subgrade. Figure 8 shows the relationship between the dry density and moisture content of the soil.

It has been observed that as the percentage of fiber in the soil increases, the maximum dry density and ideal moisture content of the soil containing the fibers change. It has been found that the ideal moisture content rises and the maximum dry density decreases as the fiber content increases. The results are presented in Tables 3 and 4.

Adding fiber to soil will render it more resistant to compaction; hence, density decreases even more when the effort required to compact the fibers-mixed specimen is equal to that of the unmixed soil specimen. Additionally, there will be an increase in moisture absorption.

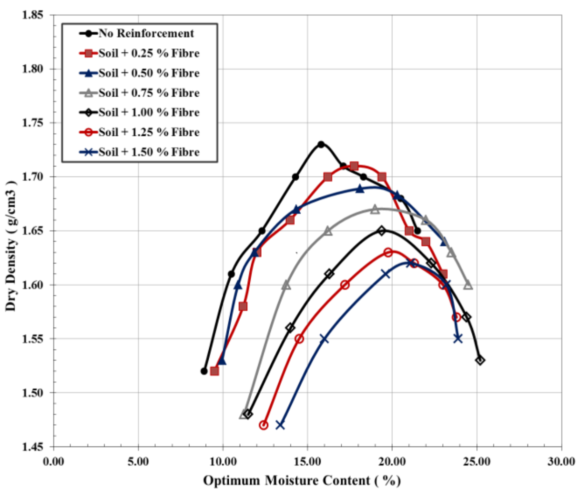

Fig. 8. Compaction properties with different percentage of Polypropylene Fibers.

Table 3. Effect of Polypropylene Fibers added to the subgrade soil on the values of MDD.

Fiber contents	MDD before reinforced (g/cm^3)	MDD after reinforced (g/cm^3)	MDD Reduction (%)
Soil + 0.25 % Fiber	1.73	1.72	058
Soil + 0.50 % Fiber	1.73	1.69	2.31
Soil + 0.75 % Fiber	1.73	1.67	3.47
Soil + 1.0 % Fiber	1.73	1.65	4.62
Soil + 1.25 % Fiber	1.73	1.63	5.78
Soil + 1.50 % Fiber	1.73	1.62	6.36

Table 4. Effect of Polypropylene Fibres added to the subgrade soil on the values of OMC.

Fiber contents	OMC before reinforced (%)	OMC after reinforced (%)	OMC Increase (%)
Soil + 0.25 % Fiber	15.8	17.75	12.34
Soil + 0.50 % Fiber	15.8	18.1	14.56
Soil + 0.75 % Fiber	15.8	19.0	20.25
Soil + 1.0 % Fiber	15.8	19.4	22.78
Soil + 1.25 % Fiber	15.8	19.75	25
Soil + 1.50 % Fiber	15.8	21.10	33.54

3.2. The effect of reinforcement using sika fibers on unconfined compressive strength.

The compressive strength of the fibber-mixed soils was significantly higher than that of the unmixed soils. When mixed with 1.0 percent Polypropylene fibbers, the unconfined compressive strength (UCS) increases by 66.44%, ranging from 1.00 to 2.98 Kg/cm^2. This increase is caused by the titanium chloride reactions from polypropylene interacting with the Ca++ from the soil to generate calcium silicate hydrate (CSH), a component of cementations, in the polypropylene-soil mixture, which increases strength. The interaction of the fibbers with the soil, which raises its shear characteristics, essentially causes the strength increase. Figure 9 shows the relationship between the soil stresses–strain behavior when it is mixed Polypropylene fibbers.

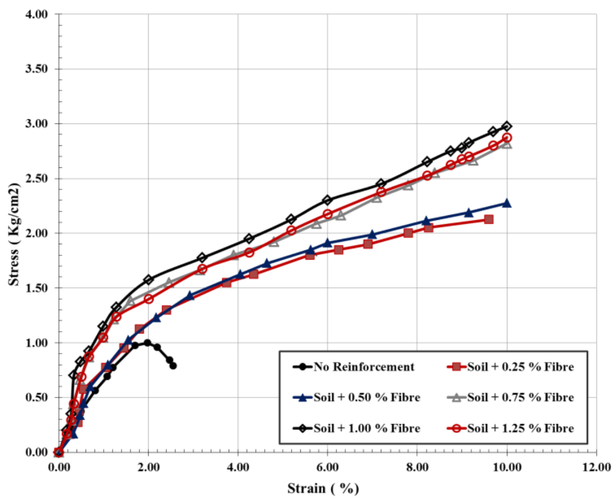

Fig. 9. Unconfined compressive strength test result with different percentage of Polypropylene Fibers.

3.3. Sika fiber reinforcement's effect on the California bearing ratio results of the test.

The CBR test is widely employed in flexible pavement design. Empirical charts are used in tandem with the test results to determine the pavement structure's thickness. The research results demonstrated that, for both soaked and unsoaked situations, a rise in the percentage of polypropylene fibers increases the CBR value up to 1.0% of polypropylene fiber content; however, the CBR value decreases with additional increases in fiber content (Figure 10).

The soil reinforced with 1.0% polypropylene fiber yielded the highest CBR value in the unsoaked state, which was 115.7% higher than the CBR value of unreinforced soil. However, in a moist situation, the CBR value of soil reinforced with the same percentage of polypropylene fiber (1.0%) is 151.19% higher than the CBR value of unreinforced soil. Tables 5 and 6 listed all the results.

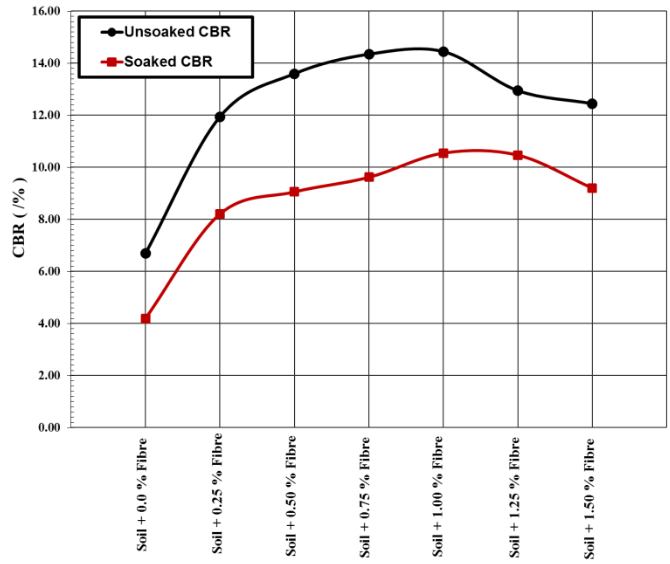

Fig. 10. CBR test result with different percentage of Polypropylene Fibers.

Table 5. Effect of Polypropylene Fibers added to the subgrade soil on CBR value for unsoaked condition.

Fiber contents	CBR before reinforced (%)	CBR after reinforced (%)	CBR Increase (%)
Soil + 0.25 % Fiber	6.70	11.95	78.36
Soil + 0.50 % Fiber	6.70	13.60	102.98
Soil + 0.75 % Fiber	6.70	14.35	114.20
Soil + 1.0 % Fiber	6.70	14.45	115.70
Soil + 1.25 % Fiber	6.70	12.95	93.28
Soil + 1.50 % Fiber	6.70	12.45	85.82

Table 6. Effect of Polypropylene Fibers added to the subgrade soil on CBR value for soaked condition.

Fiber contents	CBR before reinforced (%)	CBR after reinforced (%)	CBR Increase (%)
Soil + 0.25 % Fiber	4.20	8.21	95.47
Soil + 0.50 % Fiber	4.20	9.06	115.71
Soil + 0.75 % Fiber	4.20	9.62	129.04
Soil + 1.0 % Fiber	4.20	10.55	151.90
Soil + 1.25 % Fiber	4.20	10.47	149.28
Soil + 1.50 % Fiber	4.20	9.20	119.50

3.4. Effect of Sika Fibers Reinforcement on shear parameters value.

The value of shear parameters for both unreinforced and reinforced soil with polypropylene fibers was ascertained using the direct shear box. It was found that form the results of the direct shear box, there is an increase in cohesion value with the addition of the Polypropylene fiber to soil up to 1.0 % of Polypropylene fiber. It was found that the soil reinforced with 1.0 % Polypropylene fiber gives the maximum cohesion value, which has increased 108.98 % than the cohesion of unreinforced soil as shown in Figure 11. The fiber's interaction with the earth, which increases its shear characteristics, is what causes the strength to develop. Enhancing the soil's mechanical behavior is mostly dependent on the fiber's strength. A less effective fiber to soil net creation occurs when the fiber content is low because there is more space between the fibers in the composite mix. The fiber-soil system successfully formed a robust fiber-soil net when the fiber content was progressively raised since the distance between the fibers in the composite mix decreased. Also, fibers bridged shear cracks, reducing brittle failure. Figure 4 illustrates the types of sample failures that were noted in the lab. Because the effort required compacting the fiber-mixed soil specimen is equal to that of the unmixed soil specimen, adding fiber to the soil will increase its resistance to compaction. As a result, density decreases even more and the cohesiveness effect on soil compaction are reduced.

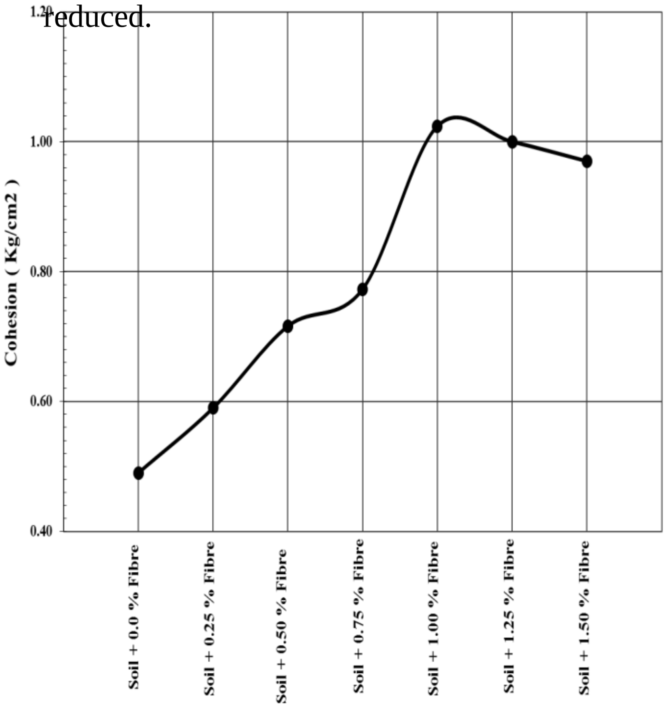

Fig. 11. Cohesion of soil with different percentage of Polypropylene Fibers.

4. New correlations between soil subgrade characteristics and the percentage of Polypropylene Fibers.

As indicated in Table 7, six different regression equations between the proportion of polypropylene fibers and the properties of the soil subgrade have been developed. The established relationships utilized to estimate soil subgrade parameters using appropriately selected fibers will be outlined and explained in the following section.

These formulas can be used to calculate the percentage change in soil characteristics. ((I-UCS), (R-γ),(I-O.M.C.), (I - C), (I – unsoaked CBR), (I – soaked CBR)) with increasing the amount of fiber used to improve the soil, without conducting any laboratory tests or numerical modeling. This can save the materials and time used to conduct these tests.

The optimum curve fitting for each relationship was determined using a variety of mathematical functions, including logarithmic, exponential, linear, second-degree polynomial, and hyperbolic. Table. 7 resulting the highest value of (R^2) from curve fittings.

Table 7. Equations relating soil subgrade characteristics to the percentage of Polypropylene Fibers added to the soil.

Eq. No.	Equation	Regression Statistics (R^2)
(1)	$(I-UCS) = -174.14 \times (Fiber\ content)^2 + 360.16 \times (Fiber\ content) + 9.125$	0.964
(2)	$(R-\gamma) = -0.5467 \times (Fiber\ content)^2 + 5.3614 \times (Fiber\ content) - 0.274$	0.990
(3)	$(I-O.M.C.) = -4.822 \times (Fiber\ content)^2 + 26.4 \times (Fiber\ content) + 2.471$	0.949
(4)	$(I-C) = -86.503 \times (Fiber\ content)^3 + 156.01 \times (Fiber\ content)^2 + 25.245 \times (Fiber\ Content) + 1.921$	0.964
(5)	$(I-\text{unsoaked CBR}) = -130.24 \times (Fiber\ content)^2 + 238.21 \times (Fiber\ content) + 11.49$	0.928
(6)	$(I-\text{soaked CBR}) = -137.45 \times (Fiber\ content)^2 + 277.64 \times (Fiber\ content) + 11.983$	0.945

4. 1. The relationship between Polypropylene Fibers Percentage and increase in UCS (I-UCS).

Figure 12 was used to examine the relationship between increases in UCS (I-UCS) and the proportion of polypropylene fibers. With a coefficient of determination of R2 = 0.964, 2nd degree polynomial equation (Eq. 1 in Table 7) showed a very high degree of relationship between them.

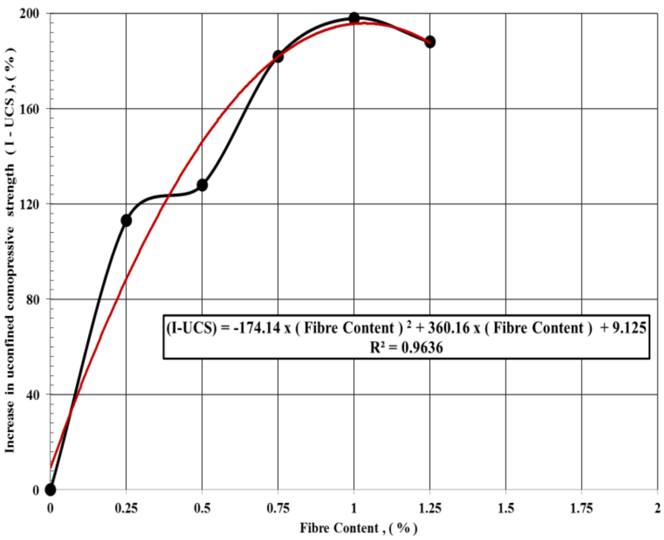

Fig. 12. Increases in UCS variation as a function of the quantity of fiber added to the subgrade soil.

4. 2. The relationship between Polypropylene Fibers Percentage and reduction in MDD (R- γ).

The relationship between the percentage of polypropylene fibers and the reduction in the MDD (R-γ) was found to be precisely represented by the second-degree polynomial equation (Eq. 2 in Table 7). As seen in Figure 13, this regression analysis produced a high coefficient of determination (R^2 = 0.990).

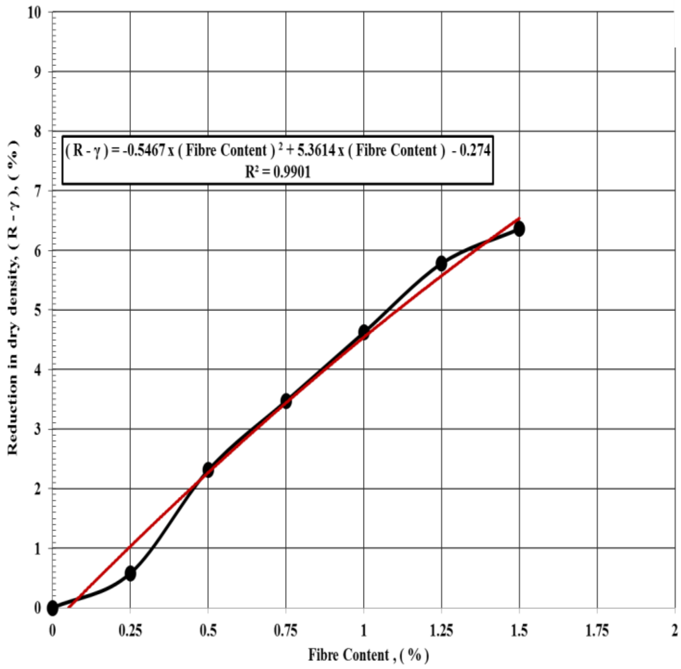

Fig. 13. Reduction in MDD variation as a function of the quantity of fiber added to the subgrade soil.

4. 3. The relationship between Polypropylene Fibers Percentage and increases in OMC (I-OMC).

Figure 14 demonstrates the relationship between increases in OMC (I- OMC) and the percentage of Polypropylene Fibers. A 2nd degree polynomial (Eq. 3 in Table 7) reflected the good correlation between increases in OMC (I- OMC) and the percentage of Polypropylene Fibers (R^2 = 0.949).

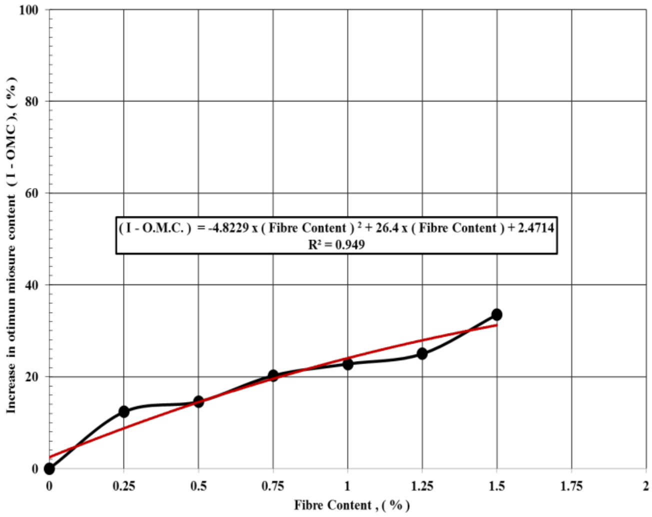

Fig. 14. Increases in OMC variation as a function of the quantity of fiber added to the subgrade soil.

4. 4. The relationship between Polypropylene Fibers Percentage and increases in cohesion (I - C).

It was found that the three-degree polynomial equation (Eq. 4 in Table 7) could accurately describe the link between the percentage of polypropylene fibers and increases in cohesion (I–C). The regression analysis showed a high coefficient of determination (R^2 = 0.964), shown in Figure 15, suggesting a substantial correlation between increases in cohesiveness (I-C) and the proportion of polypropylene fibers.

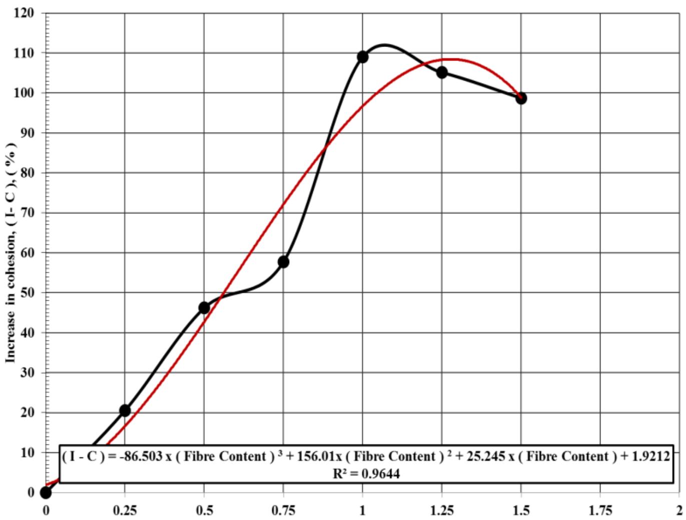

Fig. 15. Increases in soil cohesion variation as a function of the quantity of fiber added to the subgrade soil.

4. 5. The relationship between Polypropylene Fibers Percentage and increases in unsoaked CBR (I - unsoaked CBR).

Increases in unsoaked CBR (I - unsoaked CBR) were plotted against the percentage of Polypropylene Fibers, as shown in Figure 16. The research results showed that the percentage of polypropylene fibers and increases in unsoaked CBR in (I-unsoaked CBR) had a second-degree polynomial relationship. A respectable association was found via regression analysis (R^2 = 0.928, Eq. 5 in Table 7).

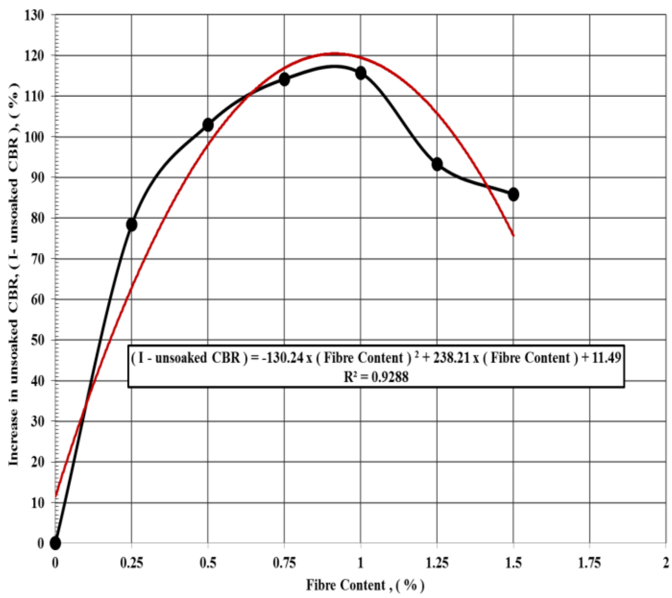

Fig. 16. Increases in soil unsoaked CBR variation as a function of the quantity of fiber added to the subgrade soil.

4. 6. The relationship between Polypropylene Fibers Percentage and increases in soaked CBR (I - soaked CBR).

Figure 17 was used to examine the relationship between increases in soaked CBR (I-soaked CBR) and the proportion of polypropylene fibers. With a coefficient of determination of R^2 = 0.45, a second degree polynomial equation (Eq. 6 in Table 7) demonstrated a very high degree of relationship between them.

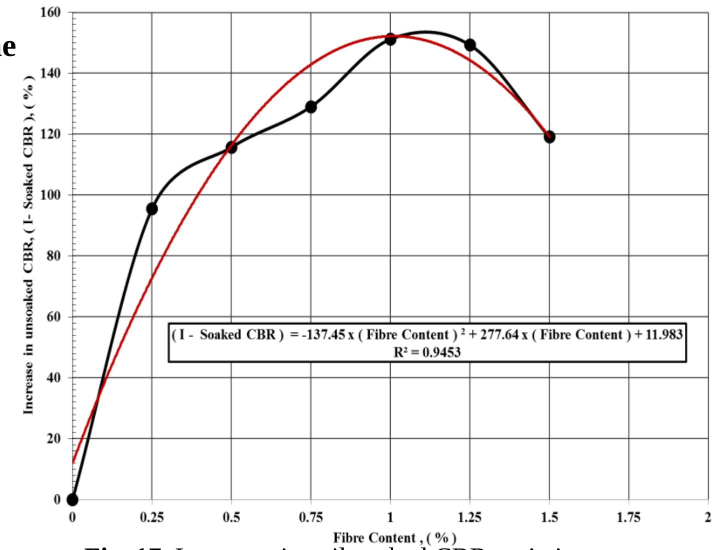

Fig. 17. Increases in soil soaked CBR variation as a function of the quantity of fiber added to the subgrade soil.

5. Economic benefits of the present study.

5.1. General.

The current study's technical and financial advantages have been established through the use of a case study. The structural design of the highway pavements was based on the American Association of State Highways and Transportation Officials (AASHTO) approach. This method was mainly used to measure the thickness of the three main layers of the pavement system: the granular subbase, granular base, and surface (asphalt cement-AC) layers.

This design process was used under real-world conditions, taking into account the 4.20% CBR value for subgrade soil. The subgrade resilience modules (M_r) of 6300 psi are provided by this CBR value (4.2%) according to ECP-1998.

The process was then repeated with similar data, with the exception of the subgrade CBR value, which was determined to be 10.55 percent (value obtained by reinforced subgrade soil with polypropylene fiber up to 1 % dosage in this investigation). With this CBR rating (10.55%), subgrade resilience modules (M_r) of 15825 psi are provided.

A flexible pavement structural number (SN) sufficient to support the estimated design ESAL can be found using the AASHTO approach. Table 8 summarizes the input data.

$$SN = a_1 \times D_1 + a_2 \times D_2 \times m_2 + a_3 \times D_3 \times m_3$$

(7) ECP-1998.

$$log_{10}(W_{18}) = Z_R \times S_0 + 9.36 \times log_{10}(SN+1) - 0.2 + \frac{log_{10}\left(\frac{\Delta PSI}{4.2-1.5}\right)}{0.4 + \frac{1094}{(SN+1)^{5.19}}} + (2.32 \times log_{10}(M_r) - 8.07)$$

(8) ECP-1998.

Where:

a_1 , a_2 , a_3 : layer coefficient of asphaltic layer, base layer, and subbase layer respectively.

D_1, D_2 , D_3 : layer thickness of asphaltic layer, base layer, and subbase layer respectively.

Z_R: standard normal deviation.

m_2 , m_3 : drainage coefficient of base layer and subbase layer respectively.

W_{18}: predicted number of 80 KN (18,000 lb) equivalent single axle loads (ESALs).

So : Overall standard deviation of design.

M_r: resilience modules.

Δ PSI: The difference between the initial design serviceability index and the design terminal serviceability index is equal to $p_o - p_t$, where p_o stands for the initial design serviceability index and p_t for the terminal serviceability index.

SN: Structural number indicative of the total pavement thickness.

Table 8. Values for equations 7 and 8 parameters are used in this study.

Description	Layer Coefficient	Drainage Coefficient	CBR (%)	Elastic Modulus, psi
AC Layer	0.44	----	----	450000
Granular Base	0.14	0.90	100	30000
Granular Subbase	0.11	0.80	30	15000
Unreinforced Subgrade	----	----	4.2	6300
Reinforced Subgrade	----	----	10.55	15825
Constant design data	W_{18} = 6000000, p_o = 4.5, p_t = 2.5, Δ PSI = 2.0, So = 0.45, Z_R = -1.645			

5.2. Soil Strength's Influence on Pavement Layers

Any research work aims at technical assistance, development and improvement, but economic effect remains the most important in the presence of the economic suffering. The importance of scientific research is that it can help governments to save money spent on infrastructure projects. To show the economic effect of this research, an illustrative case study was carried out to calculate the pavement thickness for unreinforced and reinforced soil subgrade soil using Polypropylene Fibers.

The thickness of the asphaltic layer was reduced for this case study from 6 inches for the untreated subgrade to 4.5 inches for the treated subgrade. Additionally, both untreated and treated subgrade situations, the base thickness were reduced from 8 in to 5 in. There is 25 % reduction in the thickness of AC layer, 37.5 % reduction in the thickness of base layer when subgrade soil is reinforced with polypropylene fibre. Reducing the thickness of these layers can significantly lower the project's overall cost without compromising the pavement system's strength.

- If previous results are applied on a 100 - km-highway, as an example.
- The highway consists of two directions in each direction.
- The highway consists of three laness in each direction.
- There are three lanes saving in AC Layer (m^3) equals (value of reduction in slab depth ×Road length × no. of lanes× lane width) = (25/100) × (100×1000) × (6×3.5) = 525000 m^3,
- In addition saving in base layer = (37.5/100) × (100×1000) × (6×3.5) = 787500 m^3.

6. Conclusions.

The performance of soil subgrade reinforced with polypropylene fibers was evaluated by laboratory model testing. The study's suggested conclusions are as follows:

1. The research results indicated that for each one percent polypropylene fiber concentration, the maximum dry density dropped by 6.36% and the optimal amount of moisture increased by 33.54%.
2- The unconfined compressive strength increases by 66.44 %, when mixed the soil subgrade with one percent Polypropylene fibers. Clearly, the fiber's strength has a significant impact on the soil's improved mechanical behaviour.
3- It was found that the soil reinforced with 1.0% polypropylene fiber gives the highest CBR value, which is 115.7% higher than the CBR value of unreinforced soil in an unsoaked condition. In a soaked condition, however, the CBR value of the soil reinforced with the same percentage of polypropylene fiber (1.0%) is 151.19% higher than the CBR value of unreinforced soil.
4- The soil subgrade cohesion improves 108.98 % up to 1.0 % of polypropylene fiber than the cohesion of unreinforced soil.
5- Therefore, this study focuses at both using polypropylene fibers to improve the subgrade soil in the most advantageous way possible and offering us other economical choices.
6- The study provided a novel set of correlation equations for evaluating the properties of the soil subgrade in relation to the amount of polypropylene fibers.
7- The effect of increasing sub-grade reaction deceases the AC layer depth and base layer depth, hence it can help governments to save money spent on infrastructure projects.
8- When subgrade soil is reinforced with polypropylene fiber, the thickness of the base layer is reduced by 37.5% and the thickness of the AC layer by 25%.
9- The addition of polypropylene fibers makes construction easier and more economical by using less building material.

7. Recommendations for Future Work.

The current study uses an experimental design to investigate how an increase in the content of polypropylene fibers improves subgrade soil. The following situations could be added to the study in the future:

- The research can be conducted on a range of soils with various characteristics.
- To make a more sensible engineering decision, the study can be conducted on a variety of fibre types, such as glass fiber.
- In this study, experimental work was carried out, this study can be conducted using theoretical programs such as: Plaxis, Midac, Flac, and Geostudio programs to simulate these cases.
- The study's results can be compared with other studies that have explored different stabilization methods for soils, such as lime or fly ash.

Notations

CBR	California bearing ratio
PP	Polypropylene fiber
CH	High compressibility
L.L.	Liquid limit
P.L.	Plastic limit
P.I.	Plasticity index
Gs	Specific gravity
γ_{dry}, MDD	Maximum dry density
OMC	Optimum moisture content
C	Cohesion
q_u	Unconfined compressive strength
(I-UCS)	Increases in unconfined compressive strength
(R - γ)	Reduction in maximum dry density
(I-O.M.C.)	Increases in optimum moisture content
(I - C).	Increases in cohesion
(I - unsoaked CBR)	Increases in unsoaked CBR
(I - soaked CBR).	Increases in soaked CBR

Acknowledgements

The authors would first and foremost like to thank ALLAH, the most merciful and compassionate, for providing them with the strength to finish this effort. The Higher Institute of Engineering and Technology in Minia has a geotechnical engineering laboratory. All of the soil mechanics instructors at Minia University's Civil Engineering Department use artificial intelligence to provide helpful advice.

Declarations:

The corresponding author can provide the datasets created and/or examined during the current investigation upon reasonable request.

References.

Abd Al-Kaream, K. W., Fattah, M. Y., and Hameedi, M. K. (2022). " Compressibility and strength development of soft soil by polypropylene fiber ", International Journal of GEOMATE, 22 (93), 91-97, https://doi.org/10.21660/2022.93.3206.

Adegoke, A. H., Nxumalo, S., and Felix, O. (2025). " Performance of polypropylene fiber in compacted residual soil for pavement applications ", Discover Civil Engineering Journal, 2 (172), 2-20, https://doi.org/10.1007/s44290-025-00333-6

Aneke, F. I., Hanandeh. S., and Kalumba, D. (2023). " Evaluation of factors affecting the Performance of fiber reinforced subgrade soil characteristics under cyclic loading ", Civil Engineering Journal, 9 (8), 2046–2061, http://dx.doi.org/10.28991/CEJ-2023-09-08-015

Armeni, A., and Plati, C. (2025). "An analysis of the literature data on the impact of steel and polypropylene fibers on the thickness design of airfield concrete pavements", Eng Journal, MDPI, 6 (103), 1-18, https://doi.org/10.3390/eng6050103

Brahmachary, T. K, and Rokonuzzaman, M. D. (2018). " Investigation of random inclusion of bamboo fiber on ordinary soil and its effect CBR value ", International Journal of Geo-Engineering, 9 (10), 2–11, https://doi.org/10.1186/s40703-018-0079-x

Bu, F., Liu, J., Song, Z., Sun, M., Wang, Z., Jing, M., and Qian, W. (2024). "Enhancement of water-retaining property and cracking resistance of soil under wetting-drying cycles: synergistic effect of sisal fiber and polyacrylamide ", Construction and Building Materials Journal, 435(12), 5-18, https://doi.org/10.1016/j.conbuildmat.2024.136841

Balreddy, M., Sajjan, S. S., Pruthviraja, D., and Naganna, S, R. (2024). " Utilization of alkali- treated areca fibers for stabilizing silty sand soil for use in pavement subgrades: analysis using iitpave software ", Emergent Materials Journal, 7, 1927–1939. https://doi.org/10.1007/s42247-024-00710-4.

Center of Housing and Building Research (2001). " Egyptian code for soil mechanics and foundations design - ECP. 202-2001 ", The Arab Republic of Egypt, Ministry of Housing, Utilities and Urban Communities, Part Two: Laboratory tests, 2007 Edition.

Center Housing and Building Research (1998)." Egyptian code for the works of urban and rural roads ", The Arab Republic of Egypt, Ministry of Housing, Utilities and Urban Communities, Sixth Part: Structural Design of Roads, First Edition.

Dobrzycki, P. (2023). " The Impact of Polypropylene fibre Addition on the CBR value", Architecture Civil Engineering Environment Journal, The Silesian University of Technology, 2, 81–88, Doi : 10. 2478 /A C E E- 2023 - 0017

Kunyong, Z., and Frederick C. N. (2017). " Experimental investigation on compaction and Atterberg limits characteristics of soils: aspects of clay content using artificial mixtures ", KSCE Journal of Civil Engineering, 21 (2), Vol. 21, 546–553, https://doi.org/10.1007/s12205-017-1580-z.

Lawer. A. K, Ampadu, S. I. K., and Owusu-Nimo, F. (2021). " The effect of randomly distributed natural fibers on some geotechnical characteristics of a lateritic soil", SN Applied Sciences Journal, 3 (642), 11-22, https://doi.org/10.1007/s42452-021-04634-0

Madrid, R., Mechan,, V., Asto, L., Barboza, C., and Seclen, K. (2024). " Influence of fibers on the resilient modulus and expansion of clayey subgrade soils ", International Journal of Pavement Engineering, 25 (1), 1–11, https://doi.org/10.1080/10298436.2023.2298262

Mirzababae, M., Arulrajah, A., Horpibulsuk, S., and Aldava, M. (2017). "Shear strength of a fiber-reinforced clay at large shear displacement when subjected to different stress histories ", Geotextiles and Geomembranes Journal, 45 (5), 422-429, https://doi.org/10.1016/j.geotexmem.2017.06.002

Modha, H., and Shah, A. (2019). " Randomly distributed coir fiber effect on sub grade soil - an experimental study ", Journal on Civil Engineering, 8 (4), 1–7, DOI: 10.26634/jce.8.4.13987

Patel, S. K. (2022)." Experimental investigation of glass fiber reinforced clayey soil for its possible application as pavement subgrade material ", New Approaches in Foundation Engineering, Open access peer-reviewed chapter, DOI: 10.5772/intechopen.102802

Patel, S. K, and Singh, B. (2017). " Experimental investigation on the behaviour of glass fiber- reinforced cohesive soil for application as pavements material ", International Journal of Geosynthetics and Ground Engineering, 3 (13), 1–12, DOI 10.1007/s40891-017-0090-x

Prathyusha, A., and Kumar, M. H. (2020). " Experimental study on the suitability of basalt fiber reinforced red soil for highway construction ", International Journal for Research Trends and Innovation Journal, 5 (1), 33-38, IJRTI2001008, www.ijrti.org

Product Data Sheet (2024). " Monofilament polypropylene fibers – sika Fiber ", 1st industrial zone (A), Section # 10 Block 13035, Egypt, www.sika.com.eg.

Rabab'ah, S., Al Hattamleh, O., Aldeeky, H., and Abu Alfoul, B. (2021). " Effect of glass fiber on the properties of expansive soil and its utilization as subgrade reinforcement in pavement applications ", Case Studies in Construction Materials Journal, 14, e00485, 1–12. https://doi.org/10.1016/j.cscm.2020.e00485.

Shamim, M. S. (2020). " An Experimental Study to Improve the subgrade soil of flexible pavement by using geosynthetic materials ", UITS Journal of Science & Engineering, 7(1), 12-26, https://research.uits.edu.bd/wp-content/uploads/2021/03/02-Article-of-Sanaullah-12-26.pdf

Singh, K. L., and Jamatia, M. (2020). " Study on pavement soil subgrade properties with reinforced fibers ". Indian Geotechnical Journal, 50 (4), 300–306. https://doi.org/10.1007/s40098-020-00425-3

Wei, J., Kong, F., Liu, J., Chen, Z., Kanungo, D. P., Lan, X., Jiang, C., and Shi, x. (2018). " Effect of sisal fiber and polyurethane admixture on the strength and mechanical behavior of sand". Polymers, Procedia - Social and Behavioral Sciences, 10 (10), 1–15, doi:10.3390/polym10101121.

Zemouli, S., Gouider,, N., Melais, F. Z., and Wissem, I. (2024), " Cement kiln dust and polypropylene fiber in expansive clay improvement ", Studies in Engineering and Exact Sciences Journal , 5 (1), 1771–1792, https://doi.org/10.1080/10298436. 2023.2298262